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FATIGUE PERFORMANCE OF A FIRE RESISTANT SYNTACTIC FOAM CORE COMPOSITE

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ABSTRACT

Eco-Core, a fire resistant syntactic foam for sandwich structures developed under the US Navy (ONR) program, was used to study its compression-compression fatigue performance at a sinusoidal cyclic load of frequency 2Hz, load ratio R = 10, 5 and density range of 0.526 to 0.541 g/cc. Under compression fatigue loading, Eco-core was found to be deformed in three stages- onset of failure (Stage-1), crush band growth (Stage-11) and the final failure (Stage-111), which was characterizing as the fatigue life of the Eco-core. Fatigue damage: onset and growth that leading to final failure were happened mostly in the middle or edge of the specimens. This failure behavior is same as that of static loading. The fatigue stress-life (S-N) data showed that the endurance limit (based on 1 million cycles) for final failure was $0.76S_o$ and $0.82S_o$ for stress ratio of 10 and 5, respectively. Fatigue life was found to be less sensitive to R ratio when expressed in terms of stress range versus number of load cycles that is similar to metallic materials.

Keywords: Eco-Core, Syntactic Foam, Compression-Compression, Fatigue, Failure Mechanism, Life Prediction

1. INTRODUCTION

Fire has been a major problem for both mobile (mass transit and marine) and immobile (buildings and civil infrastructure) structures. With the wide use of polymer composites in structural applications, potential for fire hazards has significantly increased. Although fire cannot be completely eliminated, it can be mitigated to reduce the loss of life and property. Extensive research is being conducted to assess and improve fire safety of composite materials for various applications [1]. A fire resistant core material called “Eco-Core” was developed [2-3] for composite sandwich structural application. The Eco-Core is made by a syntactic process using flyash and a very small amount of phenolic resin. The small volume of resin in a large volume of fly ash (ceramic microballoon) is what makes this material to be fire resistant. Mechanical, fire, toxicity and water absorption properties of Eco-Core were found to be safe and superior [2-4]. All transportation structures are subjected to cyclic loading; understanding fatigue strength, fatigue life and the associated failure modes are of great importance for structural applications. A detailed research is underway to understand the fatigue performance of Eco-Core under compression, flexure and shear loading conditions. The test specimen considered is shown in Fig.1. This paper investigates the compression-compression fatigue response of Eco-Core and a preliminary result of this study was presented at the 51st AIAA conference [5].

2. ECO-CORE MATERIALS

Eco-Core is made from a class of fly ash known as Cenosphere grade XL 150 supplied by Sphere Services Inc., a phenol-formaldehyde resole resin, Durite SC 1008 supplied by Mektech Composities Inc. The detailed processing of the material is described in reference [3]. The test specimen (Fig.1a) is a cylinder of 28 mm diameter and 25 mm height and the specimen is extracted from a panel of 360x360 mm with a thickness of 25 mm. Bulk density of all the specimen were measured and recorded. Specimens of density between 0.53 and 0.54 g/cc were selected for testing. Selected specimens for fatigue test are listed in Tables 1 and 2 for R=10 (Panel 1) and 5 (Panel 2), respectively.

3. COMPRESSION TEST AND TEST RESULTS

The static compression test was performed using an MTS servo-hydraulic test machine. The specimen was compressed between two platens at a constant displacement rate of 1.27mm/min while load and displacement were recorded at every half of one second. Compression stress and strain were calculated and plotted in Fig.2 for all five test samples (panel 1).

The stress-strain response is almost linear till the maximum stress is reached. After that stress suddenly drops or remain constant with increase in strain up to 30%, then stress gradually decrease with increase in strain and finally materially crushes. Each of these of steps, respectively, are initiation of compression failure

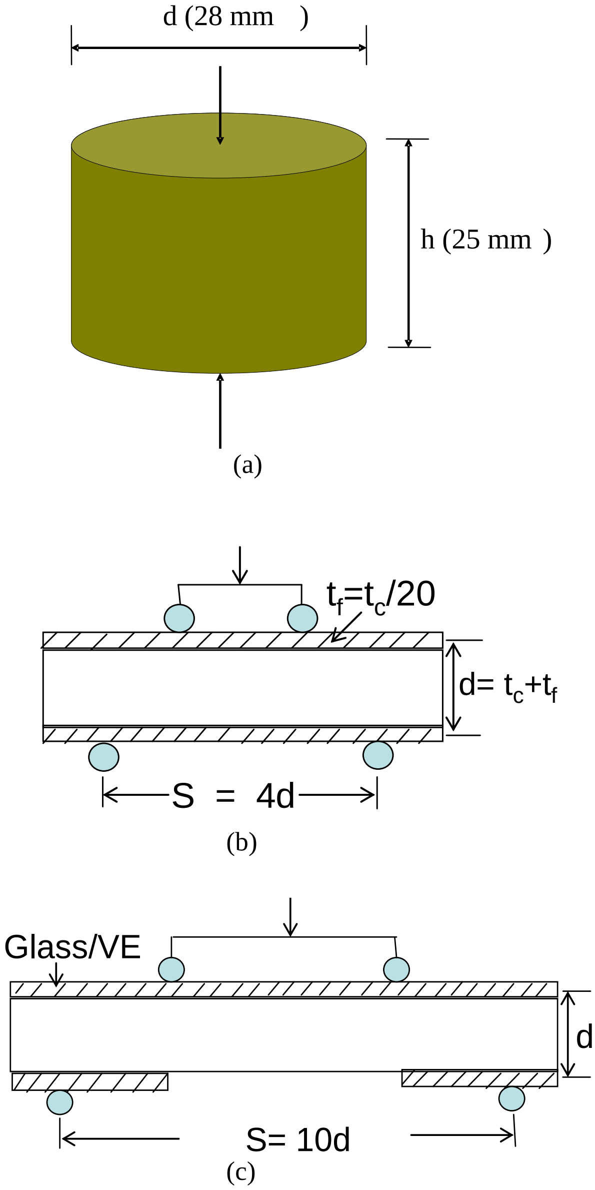

Fig 1. Test Plan: (a) Compression (b) Shear and (c) Flexure

by breakage of binder around the microbubble, which generally starts at the mid height or edge of the specimen, that is also called as formation of crush band, followed by progression band in thickness direction and leading collapse. The average compressive strength (S_o) was -18.9MPa, with a standard deviation (STD) of 0.28MPa, and average modulus was 1.74GPa with a STD of 0.11 GPa for panel 1. Whereas for panel 2, S_o was -20.3MPa with a STD of 0.45 MPa and average modulus of 1.55GPa with a STD of 0.11GPa for panel 2.

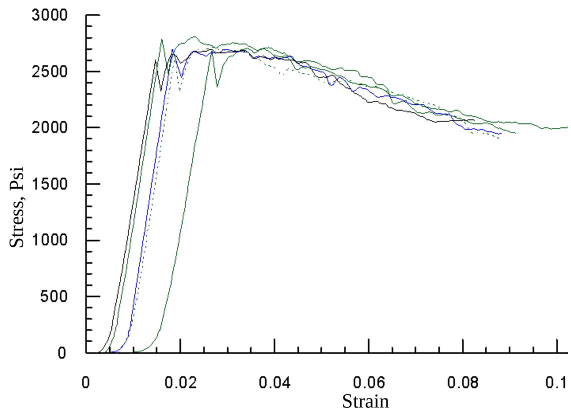

Fig 2. Compression stress-strain response

4. COMPRESSION-COMPRESSION FATIGUE TEST AND RESULTS

4.1 Fatigue Test

Compression-compression fatigue tests were conducted under a sinusoidal cyclic load of frequency 2Hz and two stress ratios of R = 10 and 5 for panel 1 and 2, respectively. Six different stress levels (S_{min}/S_0) in the range of 0.6 to 0.9 for panel 1 and four different stress levels in the range of 0.8 to 0.95 for panel 2 was used. The same setup used for static test was used for fatigue test. Here, S_{min} is the maximum applied compressive stress in the fatigue cycle and S_0 is the average static compression strength of Eco-Core. Three to four specimens were tested for each load ratio. All the tests were performed in the thickness direction of the panel. Both load and displacement data were collected using a PC based acquisition system. The displacements recorded during cyclic loading were converted into the compliance; ratio of change in displacements between the consecutive maximum and minimum loads and the loads difference. The fatigue life is defined as the number of cycles to ultimate failure. The fatigue limit is taken to be 10^6 cycles. To investigate the macro-scale fatigue mechanisms, a digital camera was set up to record the deformation sequence and images were taken only for selectively intervals between beginnings of the test to final unstable failure. The image sequences were then analyzed to understand the basic fatigue failure mechanism at the macro-scale.

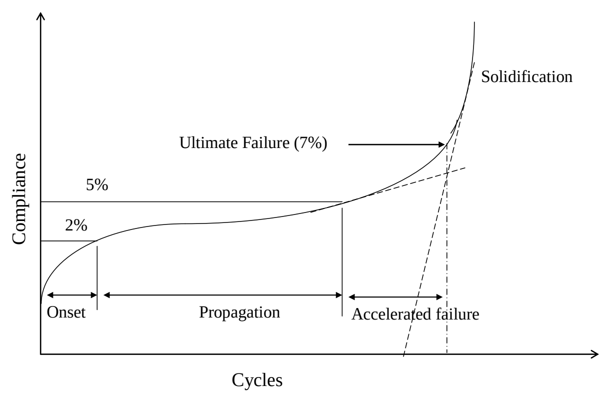

Fig 3. Three failure stages

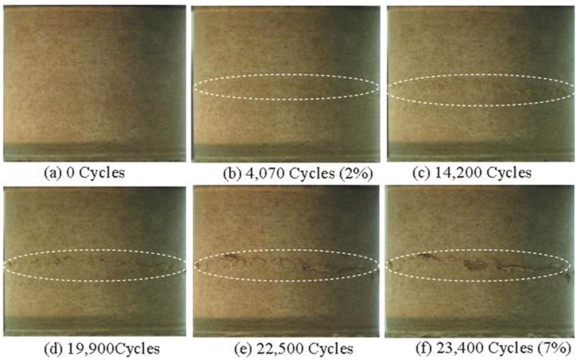

Fig 4. Initiation and successive fatigue failure

4.2 Test Results and Discussion

Under compressive fatigue loading, Eco-Core was found to be undergoing three stages of failures. Stage-1 is the damage onset, where the compliance change is about 2%. During this stage, bond between the microbubbles begin to fail. Stage-2 is associated with the formation of crush band and progression of the bad in thickness direction, which is associated with 2-5% compliance change. Stage-3 is associated with abrupt increase in compliance that is leading to ultimate failure. This stage is characterized by 5 to 10% change in the compliance, however we chose 7% compliance increase as the final failure. Fig.3 shows a typical compliance versus cycles plot with three stages of failures marked and the associated damage pattern in fig.4. The damage sequence were similar for all the tests both R= 10 and 5. Therefore, we conclude that the formation of crush band, progression and final collapse of crush bands is the compression fatigue failure mode of Eco-Core. The collapse of the material was not apparent in the region outside of the crush band which happens mostly in the middle or edge (top or bottom) of the specimens based on the weak region in the specimen. This behavior is similar to that of static failure of Eco-Core. The fatigue lives for each of the three failure criteria for all tests are listed in tables 1 and 2 for R= 10 and 5 respectively.

Table 1: Compression- compression fatigue test result for R=10, Panel 1 (S_o = -18.9 MPa)

Specimen ID	S_{min}/S_o	Cycles to failure	Residual Strength,	Cycles for Compliance Change		
				2%	5%	7%
M-14	0.9	914	-	295	740	820
M-24		1615	-	325	920	1480
M-61		602	-	65	390	520
M-56		4290	-	2,070	3820	4150
M-10	0.85	16,013	-	1,400	11650	13800
M-15		20,139	-	3,700	8,900	17,020
M-18		24,843	-	2,800	21,300	23,300
M-52	0.8	71,212	-	7,000	43,900	60,400
M-13		118,008	-	53,000	112,200	116,600
M-12		282,261	-	116,000	264,000	273,000
M-62	0.75	543,712	-	334,000	520,000	538,500
M-16		906,328	-	832,000	882,000	895,000
M-48		No*	18.155	725,000		
M-50	0.7	No*	18.727			
M-20		No*	17.796	650,000		
M-34		No*	19.692			
M-21	0.6	No*	18.541			
M-25		No*	16.155			

* Indicates no failure

Figure 5 represents the S-N curves of Eco-core for onset (2%), propagation (5%) and final failure (7 %) for R=10. Fatigue stress versus load cycle of Eco-Core follows a well defined power law equation. Constants of the equations were established for three stages of failures and listed in Table 3. Based on Figure 5, endurance limit $(N\geq10^{6})$ is estimated to be about $0.72S_o$ for onset, about $0.75S_o$ for propagation and about $0.76S_o$ for final failure for R=10.

Same analysis was performed for R= 5 as shown in figure 6, constants were determined and also listed in Table 6. Estimated values of endurance limit were about $0.80S_o$, $0.82S_o$ and $0.82S_o$ for onset, propagation and final failure, respectively. To study the R ratio effect, S_{min}/S_o versus N data in Table 1 and 2 is transferred to normalize stress range ($\Delta S/S_o$) Versus N and plotted in Figure 7 for both R=10 and 5 for damage on-set (2% compliance change) failure. The two data are closer to each other with a slightly different slope. Therefore, we can conclude that the cyclic stress range is a primary parameter that controls the fatigue life of Eco-Core and it is almost independent of stress ratio similar to metallic materials.

Table 2: Compression- compression fatigue test result for R=5, Panel 2 (S_o = -20.3 MPa)

Specimen ID	S_{min}/S_o	Cycles to Failure	Residual Strength,	Cycles for Compliance Change		
				2%	5%	7%
M-46	0.95	2,318	-	570	1,920	2,140
M-30		2,497	-	1,850	2,240	2,410
M-55		10,057	-	5,800	8,800	9,500
M-39	0.90	9,053	-	4,300	7,350	8,500
M-31		2,973	-	780	2,600	2,860
M-19		4,366	-	1,500	4,090	4,250
M-52	0.85	119,663	-	67,000	113,500	117,550
M-44		No*	21.464			
M-51		33,587	-	21,300	31,350	32,400
M-27	0.80	No*	20.565	250,000		
M-45		No*	20.995			
M-11		986,982	-	835,000	955,000	963,600

* Indicates no failure

Table 3: Constants in S-N equation for R=10 and 5

Load ratio, R	Failure criteria	Constants	
		A_o	α
10	2%	1.02	-0.05
	5%	1.05	
	7%	1.06	
5	2%	1.05	-0.041
	5%	1.09	-0.046
	7%	1.09	-0.047

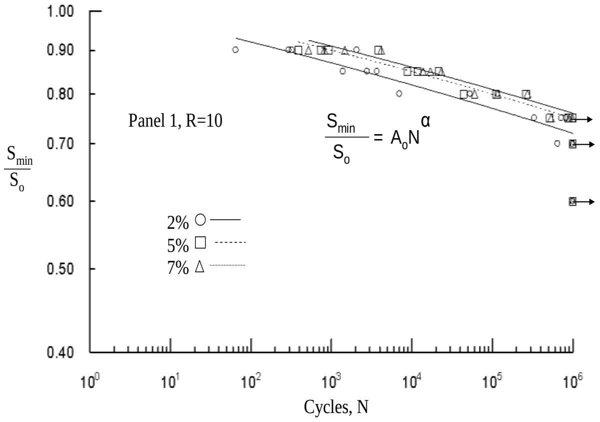

Fig 5. S-N curves for 2%, 5% & 7% compliance change for R=10

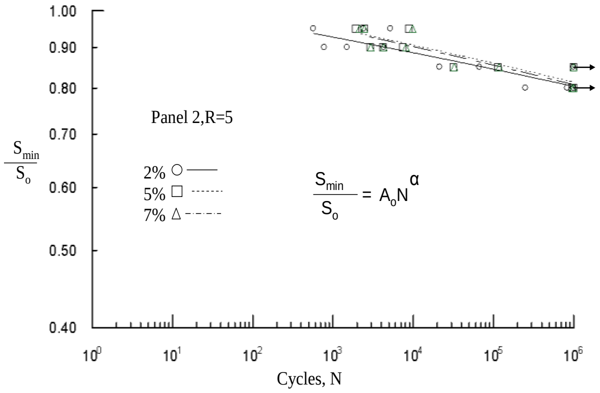

Fig 6. S-N curves for 2%, 5% & 7% compliance change for R=5

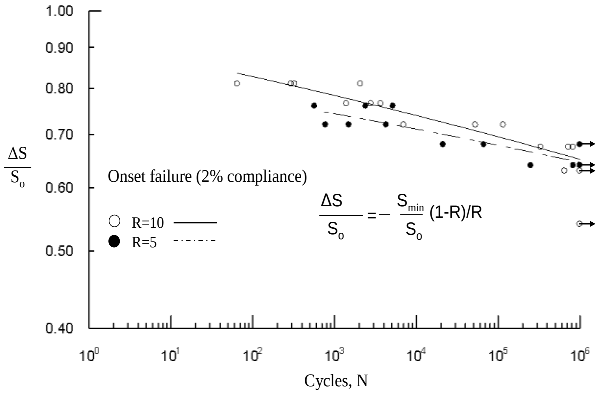

Fig 7. Normalized stress range versus N for 2% compliance change for R= 10 and 5.

5. CONCLUSION

The study showed Eco-core has well defined fatigue failure modes in cyclic compression. The failure is characterized by formation of a single crush band at the middle or edge of the specimen (at about 2% compliance change), than crush band propagation leading to the final failure. The three failure modes were found to be same for static and fatigue loading. Endurance limit (based on 1 million cycles) was $0.72S_o$, $0.75S_o$ and $0.76S_o$, respectively for on-set, propagation and final failure for R=10 while it is $0.81S_o$, $0.82S_o$ and $0.82S_o$, for R=5. Fatigue life was found to be less sensitive to R ratio when expressed in terms of stress range versus number of load cycles that is similar to metallic materials.

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